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Please change the subject document, titled *Preliminary Analysis for a Mach 8 Crossflow Transition Experiment on the Pegasus Space Booster* by Leslie Gong, W. Lance Richards, Richard C. Monaghan, and Robert D. Quinn as indicated below.

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Page 10	Page 10

Gregory A. Shell

NASA Technical Memorandum 104272

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PRELIMINARY ANALYSIS FOR A MACH 8 CROSSFLOW TRANSITION EXPERIMENT ON THE PEGASUS® SPACE BOOSTER

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ABSTRACT

A boundary-layer transition experiment is proposed for a future flight mission of the air-launched Pegasus® space booster. The flight experiment requires attaching a glove assembly to the wing of the first-stage booster. The glove design consists of a spring and hook attachment system which allows for thermal growth of a steel 4130 skin. This paper presents results from one- and two-dimensional thermal analyses of the initial design. These analyses were performed to ensure the integrity of the wing and to define optimal materials for use in the glove. Results obtained from the thermal analysis using turbulent flow conditions showed a maximum temperature of approximately 305 °C (581 °F) and a chordwise temperature gradient of less than 8.9 °C/cm (40.5 °F/in.) for the critical areas in the upper glove skin. The temperatures obtained from these thermal analyses are well within the required temperature limits of the glove.

NOMENCLATURE

CTE	Coefficient of thermal expansion, $\frac{\mu\text{cm}}{\text{cm }^\circ\text{C}}\left(\frac{\mu\text{in.}}{\text{in.}^\circ\text{F}}\right)$
C_p	specific heat, $\frac{\text{J}}{\text{kg K}}\left(\frac{\text{Btu}}{\text{lb }^\circ\text{F}}\right)$
E	modulus of elasticity, GPa (Msi)
FS	fuselage station, cm (in.)
k	thermal conductivity, $\frac{\text{W}}{\text{m K}}\left(\frac{\text{Btu}}{\text{hr ft }^\circ\text{F}}\right)$
LE	leading edge
LTA	Lockheed Thermal Analyzer
q	heat flux, $\frac{\text{W}}{\text{m}^2}\left(\frac{\text{Btu}}{\text{ft}^2\text{ sec}}\right)$
T	temperature, °C (°F)
T_∞	radiation heat sink, °C (°F)
TE	trailing edge
X	distance measured aft from glove leading edge, cm (in.)
y	lateral coordinate measured to the right from vehicle centerline, cm (in.)
z	vertical coordinate measured up from vehicle thrust line, cm (in.)

® Pegasus is a registered trademark of Orbital Sciences Corporation, Fairfax, Virginia.

α	angle of attack, deg
σ_u	ultimate stress, MPa (ksi)
σ_y	yield stress, MPa (ksi)
ρ	density, $\frac{kg}{m^3}\left(\frac{lb}{in^3}\right)$

INTRODUCTION

The Pegasus® space booster is a three-staged rocket which is air launched from a B-52 aircraft to introduce small payloads into low Earth orbit. To understand and predict crossflow transition under hypersonic flight conditions where ground test information is unavailable, a piggyback flight experiment is proposed for the Pegasus® [1]. A cost-effective flight test technique for conducting such experiments involves designing and building a temporary test structure, called a glove, and installing it over part of the existing wing. This technique avoids the need for major modifications to the primary load-carrying wing structure and simplifies the many systems required for flight test. A thermal analysis was performed to define the optimal materials for use in the glove design and to predict the glove temperature distributions for the proposed crossflow transition experiment. This paper describes the preliminary glove design and presents results from one- and two-dimensional thermal analyses.

BACKGROUND

Figure 1 shows the physical dimensions of the rocket and the proposed glove location. The overall length of the Pegasus® booster is approximately 14.9 m (49 ft) with a wingspan of 6.7 m (22 ft). The cylindrical fuselage of the rocket is approximately 1.3 m (4.2 ft) in diameter. The wing has a clipped delta planform with a 45° leading-edge sweep angle.

At an altitude of 13,000 m (42,000 ft) and Mach 0.8, the booster separates from the B-52 aircraft, descends for 5 sec, ignites, and burns for approximately 80 sec. At first-stage burnout, the booster has accelerated to Mach 8 at an altitude of approximately 61,000 m (200,000 ft). The booster follows a fixed trajectory which is predetermined for a particular payload insertion. Figure 2 shows the Pegasus® space booster mounted under the wing of the B-52 aircraft. Trajectory information from previous flights are provided in references 2 and 3.

GLOVE DESIGN

This section describes the preliminary design of the glove, including the definition of the skin materials, edge-fairing details, leading-edge attachment, and skin-attachment mechanism. Additional details of the overall glove requirements are given in reference 1.

Structural design requirements

The outside dimensions of the test surface and the fairings were defined to meet the aerodynamic experiment requirements [1]. The metallic portion of the test surface has a plan view area of 0.985 m^2 (10.6 ft^2). Aside from the usual flight loads envelope, the structural design requirements included a waviness criterion not to exceed 0.008 cm (0.003 in.) over a 5.1 cm (2 in.) length throughout the flight envelope; a requirement to minimize any step discontinuities at the inboard edge of the test surface, especially near the leading edge, and the requirement to have a thermally conductive skin. Such a skin was needed, so thermocouples mounted on the inside skin surface would sense heating changes caused by boundary-layer transition. Note that weight was not a primary design consideration, and the structure was not optimized in this regard.

Test surface design

The structural requirements resulted in a design with a relatively thick metallic outer skin and a large leading-edge heat sink (figure 3). The test skin is laid over a balsa support surface. This preshaped support is glued to the wing of the Pegasus®.

Figure 4 shows the test skin attached to the balsa-contoured surface using a series of springs spaced on 6.35-cm (2.5-in.) centers. These springs hold the skin securely to the surface but also allow it to expand thermally with only a small resistance due to sliding friction. Each spring is attached to the test skin by a 0.152-cm (0.06-in.) diameter wire loop which is brazed to the skin. A hook engages this loop, and a preload is applied through the spring to react against aerodynamic forces. Insulation placed inside the hook cavity reduces thermal radiation from the skin.

The skin is attached rigidly to the Pegasus® wing at its inboard leading edge (figure 5). The test glove leading edge is constrained to movement parallel to the Pegasus® wing leading edge by a series of slotted attachments. The glove is free to thermally expand aft and spanwise parallel to the leading edge.

Fairing design

Figure 6 shows an aerodynamic fairing used to blend the test surface into the existing wing. Figure 7 shows cross sections at locations A-A and B-B and details of the inboard and outboard fairing. This fairing is made in two parts. A hot section approximately 6 in. wide interfaces with the test surface. This section consists of fibrous silica insulation which was developed for use as part of the space shuttle thermal protection system. The final blending into the wing is done with a foam fiberglass sandwich. An ablative coating similar to that used on the Pegasus® wing is applied over the fiberglass and extends over the interface with the ceramic. The fairing on the inboard side is flush with the test surface. On the aft and outboard fairings, the test surface overlays the fairing to allow for thermal expansion.

Material selection

Several requirements were identified in the glove material selection process which significantly affected the prediction of crossflow transition. Boundary-layer transition is highly sensitive to glove shape changes during the flight experiment; therefore, the shape of the glove must be structurally stable. Local buckling or excessive thermal expansion might compromise the desired results of the experiment. Several materials were considered for the glove. These candidates are presented in tables 1(a) and 1(b) as a matrix of thermal and mechanical properties. Other factors, such as availability, machineability, and general practical applications, were also considered.

Steel 4130 was tentatively selected as the most logical candidate for the glove design. However, because of the great impact that the thermal characteristics have on the temperatures, a one-dimensional thermal model was constructed to compare the affects of these temperatures on a steel glove with those of an aluminum or a copper glove. The thermal performance of these candidate materials is described next.

A one-dimensional thermal model of an initial glove design concept was constructed to calculate temperatures at the leading edge for aluminum, copper, and steel. This initial concept consisted of a metallic skin bonded to fiberglass. In turn, this skin and fiberglass were bonded to a foam layer [1]. The foam layer is then bonded directly to the graphite-epoxy skin of the Pegasus® wing.

Figure 8 shows a sketch of this preliminary model. The model consisted of 14 nodes and included aerodynamic heating to the outer skin and radiation to space. The metallic skin was divided into eight layers with each layer having a thickness of 0.16 cm (0.063 in.). This figure also shows layers which represent the epoxy, fiberglass, and foam. The outer surface emittance was estimated to be 0.80, and radiation was to a heat sink temperature of –46 °C (–50 °F).

Three thermal analyses for aluminum, copper, and steel were performed using a finite-difference-based program called the Lockheed Thermal Analyzer (LTA) (Lockheed Corporation, Burbank, California). Figure 9 shows the three outer skin temperature time histories. Aluminum and copper resulted in the highest and lowest peak temperatures, respectively. Aluminum was eliminated as a viable material because of the high skin temperature predictions. The peak temperature difference between the copper and the steel skin analyses was only 19.2 °C (34.6 °F) on the outer skin. The temperature differences between copper and steel were small. Since copper is not a very practical structural material, selection of steel for the glove appears verified.

INPUT TO THERMAL ANALYSES

Thermal analyses were required to ensure that none of the maximum operating temperatures of the glove materials were exceeded. This section describes the procedure used to calculate appropriate parameters used as input to the one- and two-dimensional thermal analyses. The flight profile and aerodynamic heating are described next.

Flight profile

The F-2 flight trajectory [2] was used as input to calculate the heating rates used for the thermal analysis of the metallic skin. Figure 10 shows the parameters of Mach number, altitude, and angle-of-attack time histories. To date, the F-2 trajectory produced the highest heating rates of the four Pegasus® launches [2, 3]. A preliminary thermal analysis showed that the F-2 mission is significantly higher and, therefore, represents the “worst case” heating condition for the glove design.

Aerodynamic heating

Aerothermal heating rates were calculated using an in-house aerodynamic heating program called THEOSKIN. Time histories of velocity, angle of attack, and altitude were used as input parameters. This program calculates surface temperatures, heat transfer coefficients, heating rates, skin friction, and surface static pressures at discrete locations. A cross section of the outer mold line of the glove was used to determine a wedge angle and the surface locations of the node points from the thermal model. These surface locations were required to determine flow distances and expansion angles needed for heating calculations.

This program permits use of different theories for calculating heat transfer. These theories can be applied for each location of interest for laminar or turbulent flow conditions in addition to flows with transition. Transition can be input as a function of Reynolds number and local Mach number or of time. At the leading edge, the Fay and Riddell Method was used to calculate the stagnation point heating rates with sweep [4]. Swept cylinder theory was used to determine local flow conditions. Heating rate distributions around the leading edge used the Lees theory [5]. On the glove skin aft of the leading edge, local flow conditions were calculated for an attached flow using the oblique shock theory [6]. The heat transfer coefficients were calculated using Eckert's Reference Enthalpy Method [7, 8]. This method was used in calculating the heating rates for laminar and turbulent flow conditions for the upper and lower surface of the glove. Real gas properties of air were used in all calculations [9].

RESULTS AND DISCUSSION

The aerodynamic heating results were used as input to the one- and two-dimensional analyses. These analyses are described next.

One-dimensional thermal analysis

A preliminary one-dimensional model was used to determine if the spring and hook assembly would have an appreciable affect on the skin temperature calculations and, therefore, be required in the two-dimensional thermal analysis. Figure 11 shows two thermal skin models. Model 1 is the skin model without the spring and hook assembly and consists of six conduction resistors, six capacitor nodes, and one external radiation resistor. Model 2 is the skin model with the spring and hook assembly and is comprised of 19 conduction resistors, 16 capacitor nodes, and 1 external radiation resistor. The aerodynamic heating is applied to the external skin nodes as shown.

Figure 12 shows the skin temperatures of models 1 and 2. As shown, the temperature differences between the two models are negligible. The maximum difference between the calculated skin temperatures with and without the spring and hook assembly was 4.4 °C (8 °F). Based on the results of the one-dimensional analysis, the spring and hook assembly was neglected in the two-dimensional model of the glove. This simplification in the thermal model did not significantly affect the results of the two-dimensional analysis.

Two-dimensional thermal analysis

A drawing of the two-dimensional model is shown in figure 13. This model consists of 123 conduction resistors, 75 capacitor nodes, and 22 external radiation resistors. Aerodynamic heating was applied to each of the 22 external surface nodes. The outer surface emittance was estimated to be 0.8, and the external radiation was to a sink temperature of –46 °C (–50 °F). The two-dimensional thermal model of the glove was used to determine the optimum thickness of the metallic skin for minimum temperature, minimum weight, and structural integrity.

Figure 14 shows the outer mold line of the metallic glove and the locations of the thermal model nodes. Table 2 lists the distances of the nodes from the leading edge together with the overall skin thicknesses at each surface node location.

Figures 15, 16, and 17 show the results of the two-dimensional analysis. These figures show results of the temperature time histories for seven locations on the glove from X = 3.33 cm (1.31 in.) to X = 79.32 cm (31.23 in.). Figure 15 shows the results obtained when the boundary-layer flow was assumed to be all laminar. The maximum temperature for this calculation was 128 °C (262 °F), and the maximum temperature gradient was 15.1 °C/cm (69 °F/in.) between X = 3.33 cm (1.31 in.) and X = 4.88 cm (1.92 in.) at 79 sec.

Figure 16 presents the calculated temperature time histories, assuming an all turbulent boundary layer. The maximum temperature obtained was 305 °C (581 °F), and the maximum temperature gradient occurred between X = 6.48 cm (2.55 in.) and X = 11.63 cm (4.58 in.) and was 26.9 °C/cm (123 °F/in.).

Figure 17 shows the temperature time histories calculated with boundary-layer transition. The boundary layer was all laminar for locations from X = 3.33 cm (1.31 in.) through X = 11.63 cm (4.58 in.). For X locations of 28.80, 54.00, and 79.32 cm (11.34, 21.26, and 31.23 in.), these calculations were initially turbulent and transitioned to laminar flow at 40, 45, and 50 sec, respectively. The maximum temperature obtained was 131 °C (268 °F), and the maximum temperature gradient occurred between X = 3.33 cm (1.31 in.) and X = 4.88 cm (1.92 in.) and was 15.1 °C/cm (69 °F/in.).

CONCLUSIONS

Thermal analyses were performed for the preliminary design of the Pegasus® Glove Experiment. These analyses helped in the material selection for the glove as well as to predict the glove temperature distributions resulting from the Mach 8 flight trajectory. Results from several models were presented, including a one-dimensional model of the leading edge, a spring and hook thermal model, and a two-dimensional thermal model of the entire glove. The leading-edge thermal analysis results verified that steel was a more suitable metal than either aluminum or copper. The spring and hook analysis results showed that the heat transfer through the spring and hook hardware did not appreciably affect the steel skin temperatures. For critical portions of the flight between 55 and 75 sec, the temperature difference between the skin temperature with and without the spring and hook was less than 1.8 percent.

The two-dimensional thermal analysis results showed that the glove design presented in this paper meets the requirements of the proposed crossflow transition experiment. By refining the leading-edge and glove skin thicknesses of the leading edge and skin, the peak upper surface temperature was maintained below 305 °C (581 °F). Temperature gradients in the thinnest skin sections were no more than 8.9 °C/cm (40.5 °F/in.) for the three flow conditions examined.

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Table 1. Physical properties of candidate materials.

(a) SI units.

Material	Physical properties					Mechanical properties				
						Strength at 25 °C		Strength at 200 °C		
	k, $\frac{W}{mK}$	ρ, $\frac{kg}{m^3}$	C_p, $\frac{j}{kgK}$	ρC_p, $\frac{kJ}{M^3K}$	CTE, $\frac{\mu cm}{cm\ °C}$	σ_u, MPa	σ_y, MPa	σ_u, MPa	σ_y, MPa	E, GPa
Aluminum										
2024-T4	130	2768	879	2434	23.2	427	310	324	241	73
6061-T6	168	2713	963	2612	23.6	310	276	241	207	69
Copper 99.95										
Hard	391	8941	376	3369	16.6	345	310	– – –	– – –	123
Soft	391	8941	376	3369	16.6	221	76	– – –	– – –	– – –
Nickel										
Inconel X™	11.8	8304	439	3650	12.1	1069	690	1007	627	214
René 41™	11.8	8249	334	2763	11.9	1172	896	1103	876	207
Steel										
1018	51.9	7861	485	3818	12.1	379	248	– – –	– – –	207
4130	43.3	7833	477	3739	11.3	655	517	627	448	207
301,4(SS)	17.3	7916	439	3480	16.6	517	207	414	179	200
Titanium										
6Al-4V	7.3	4429	502	2225	8.8	896	827	696	579	114
5Al-2.5Sn	8.0	4484	544	2440	9.4	827	779	604	561	107

™Inconel X is a registered trademark of the International Nickel Company, Huntington, West Virginia.
™René 41 is a registered trademark of Teledyne Allvac/Vasco Marketing, Monroe, North Carolina.

Table 1. Concluded.

(b) English units.

Material	Physical properties					Mechanical properties				
						Strength at 75 °F		Strength at 400 °F		
	k, $\frac{\text{Btu}}{\text{hr ft °F}}$	ρ, $\frac{\text{lb}}{\text{in}^3}$	C_p, $\frac{\text{Btu}}{\text{lb °F}}$	ρC_p, $\frac{\text{Btu}}{\text{in}^3\ \text{°F}}$	CTE, $\frac{\mu\text{in.}}{\text{in. °F}}$	σ_u, ksi	σ_y, ksi	σ_u, ksi	σ_y, ksi	E, Msi
Aluminum										
2024-T4	75	0.100	0.210	0.021	12.9	62	45	47	35	10.6
6061-T6	97	0.098	0.230	0.021	13.1	45	40	35	30	10.0
Copper 99.95										
Hard	226	0.323	0.090	0.029	9.2	50	45	– – –	– – –	17.8
Soft	226	0.323	0.090	0.029	9.2	32	11	– – –	– – –	– – –
Nickel										
Inconel X™	6.8	0.300	0.105	0.032	6.7	155	100	146	91	31.0
René 41™	6.8	0.298	0.080	0.024	6.63	170	130	160	127	30.0
Steel										
1018	30	0.284	0.116	0.033	6.7	55	36	– – –	– – –	30.0
4130	25	0.283	0.114	0.032	6.3	95	75	91	65	30.0
301,4(SS)	10	0.286	0.105	0.030	9.2	75	30	60	26	29.0
Titanium										
6Al-4V	4.2	0.160	0.120	0.019	4.9	130	120	101	84	16.5
5Al-2.5Sn	4.6	0.162	0.130	0.021	5.2	120	113	88	81	15.5

Table 2. Skin thicknesses and locations for the two-dimensional thermal model.

(a) SI units.

Outer node number	Steel skin thickness, cm	Distance from glove leading edge, cm
82	0.229	34.47
83	0.229	22.96
84	0.229	12.34
85	0.635	6.48
86	0.635	4.88
87	0.635	3.33
1	0.953	2.11
2	0.935	1.27
3	1.070	0.58
4	1.220	0.15
5	1.270	0.00
6	1.220	0.15
7	1.070	0.58
8	0.935	1.27
9	0.935	2.11
127	0.635	3.33
126	0.635	4.88
125	0.635	6.48
124	0.229	11.63
123	0.229	28.80
122	0.229	54.00
121	0.229	79.32

(b) English units.

Outer node number	Steel skin thickness, in.	Distance from glove leading edge, in.
82	0.090	13.57
83	0.090	9.04
84	0.090	4.86
85	0.250	2.55
86	0.250	1.92
87	0.250	1.31
1	0.375	0.83
2	0.375	0.50
3	0.421	0.23
4	0.481	0.06
5	0.500	0.00
6	0.481	0.06
7	0.421	0.23
8	0.375	0.50
9	0.375	0.83
127	0.250	1.31
126	0.250	1.92
125	0.250	2.55
124	0.090	4.58
123	0.090	11.34
122	0.090	21.26
121	0.090	31.23

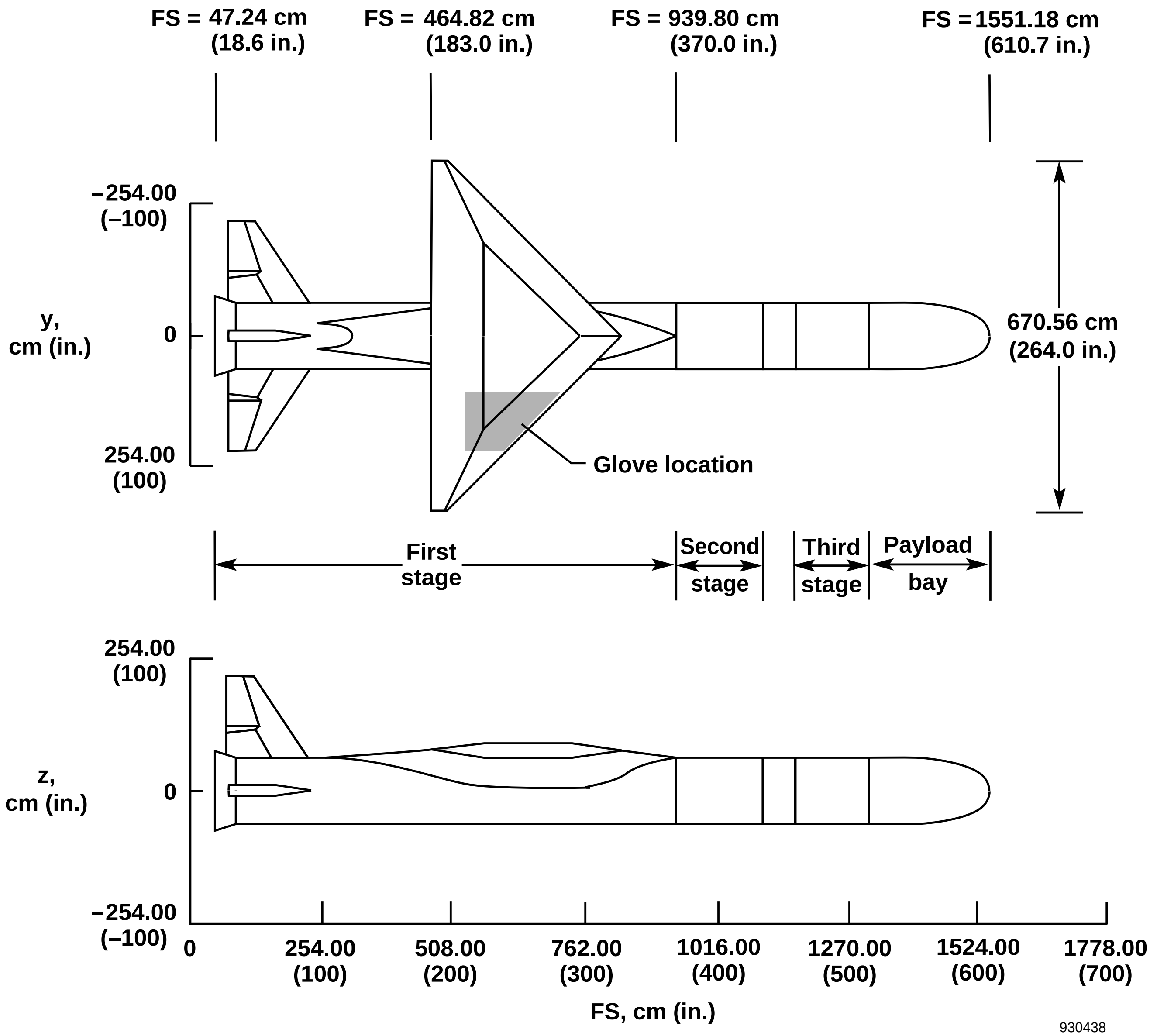

Fig. 1. Pegasus® launch configuration and proposed glove location.

Fig. 2. Pegasus® space booster mounted under the wing of a B-52 aircraft.

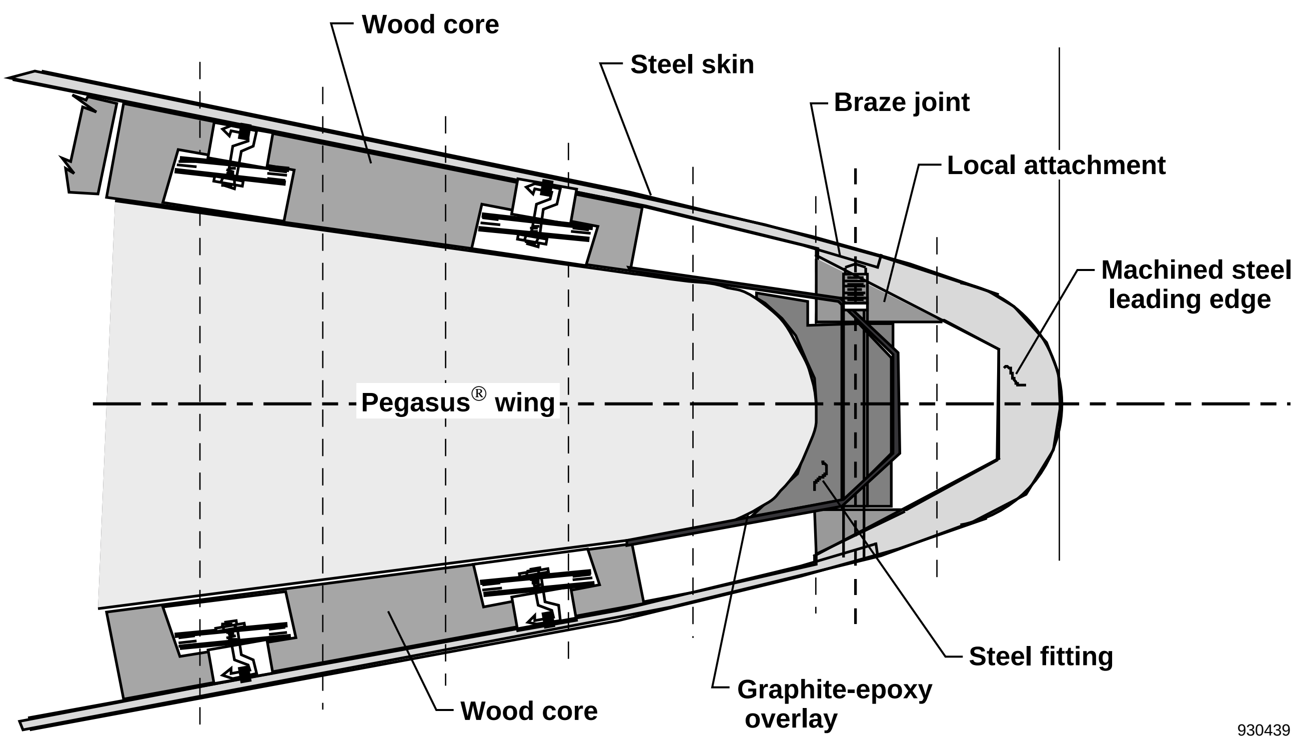

Fig. 3. Leading-edge glove structure.

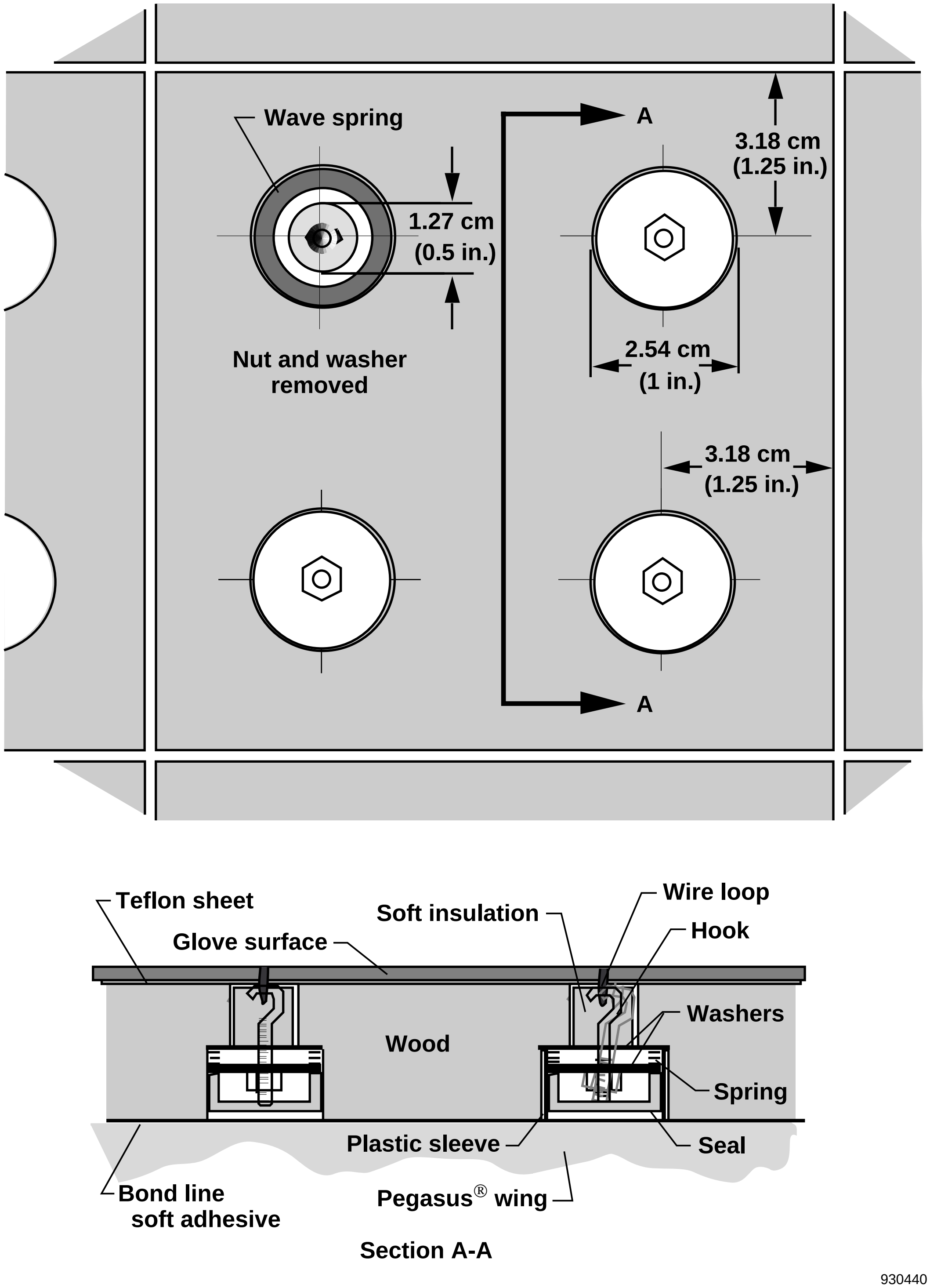

Fig. 4. Spring and hook skin attachment assembly.

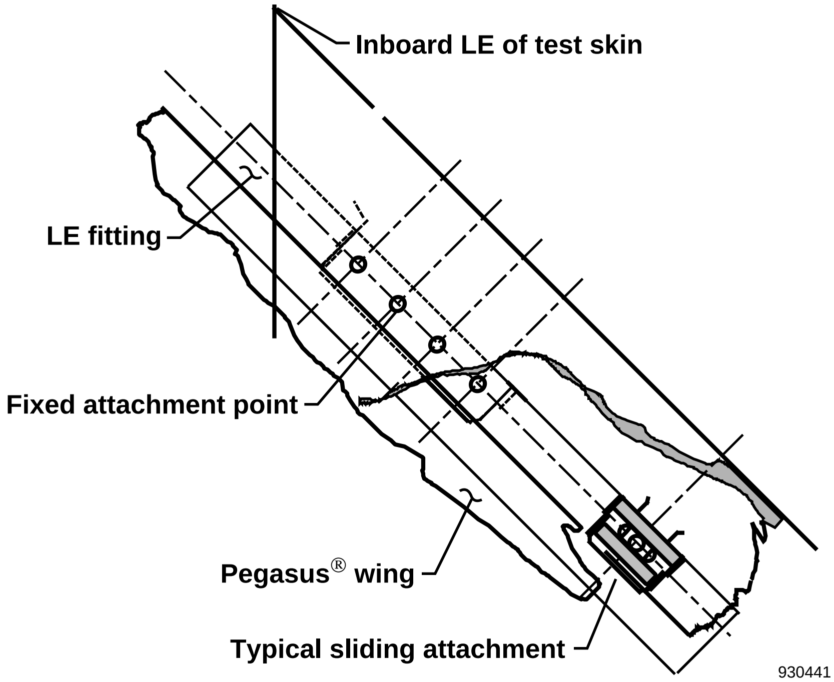

Fig. 5. Glove leading-edge-fixed and -sliding attachments.

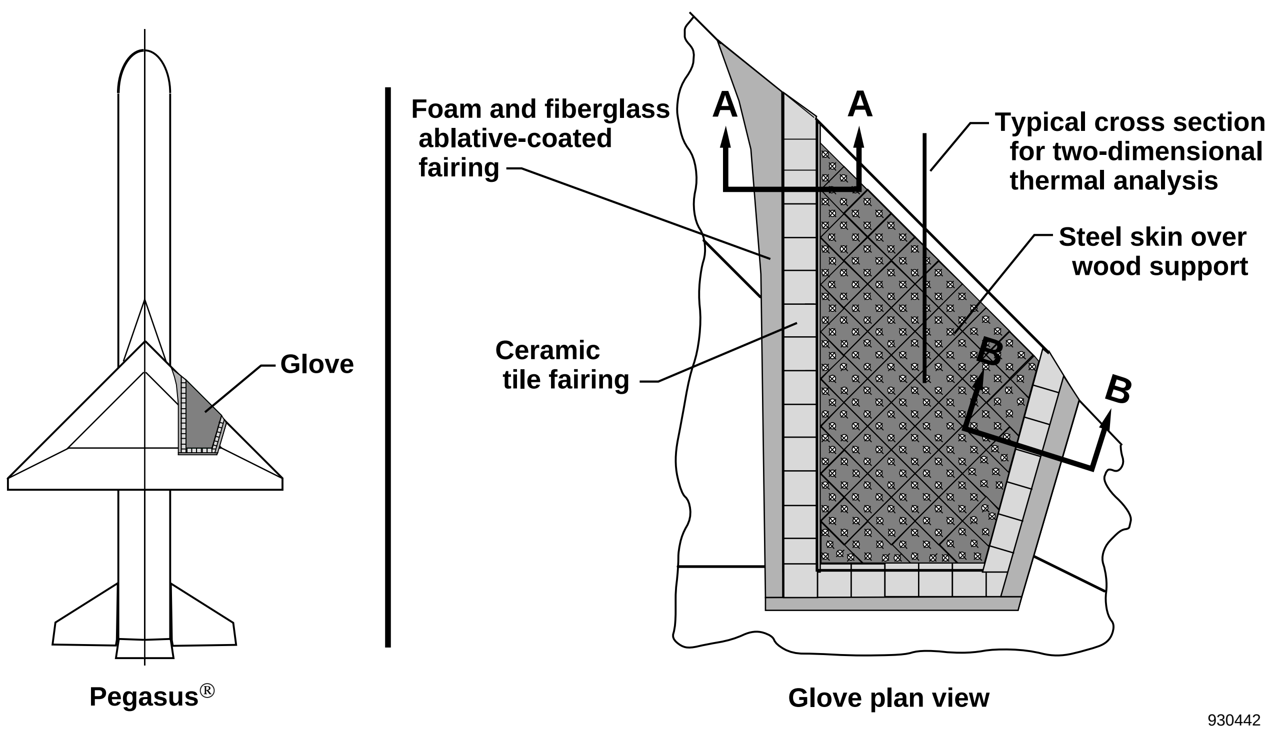

Fig. 6. Plan view of the Pegasus® booster and test glove.

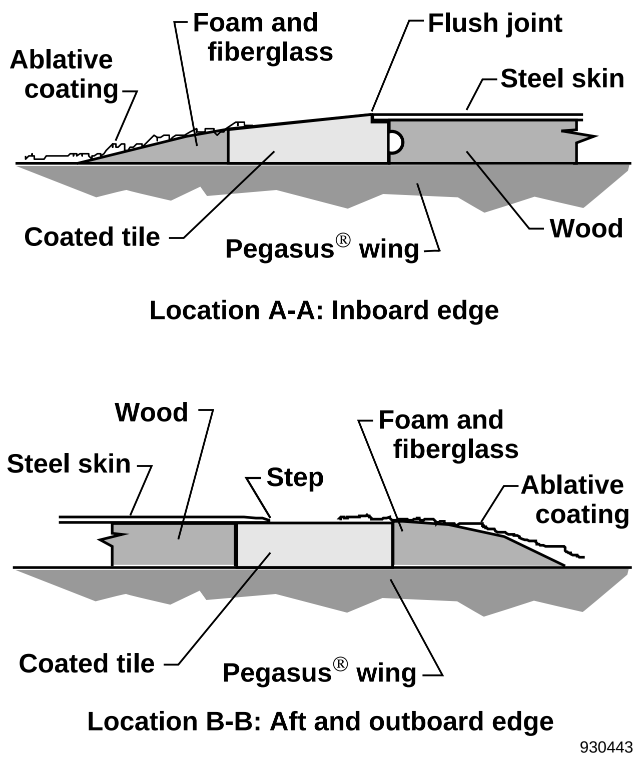

Fig. 7. Test skin edge fairings.

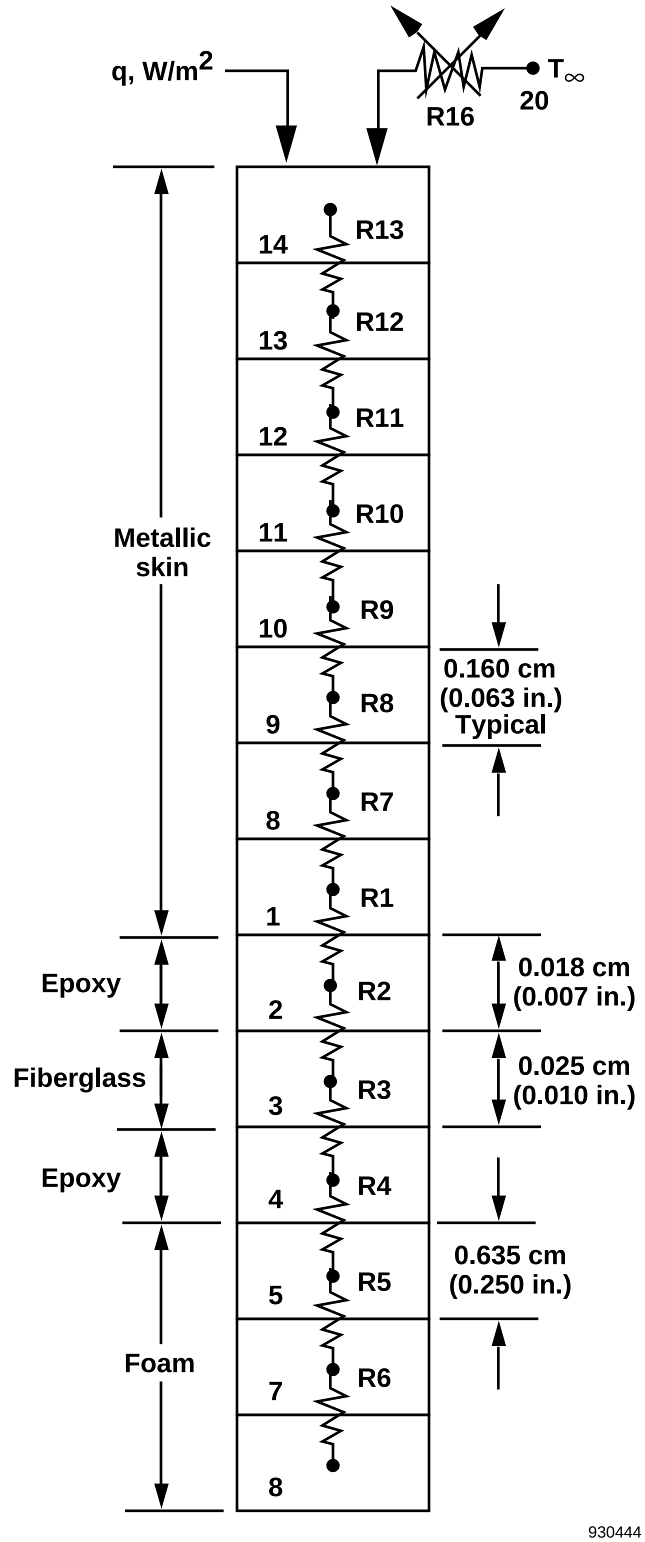

Fig. 8. One-dimensional LTA model used to predict leading-edge skin temperatures.

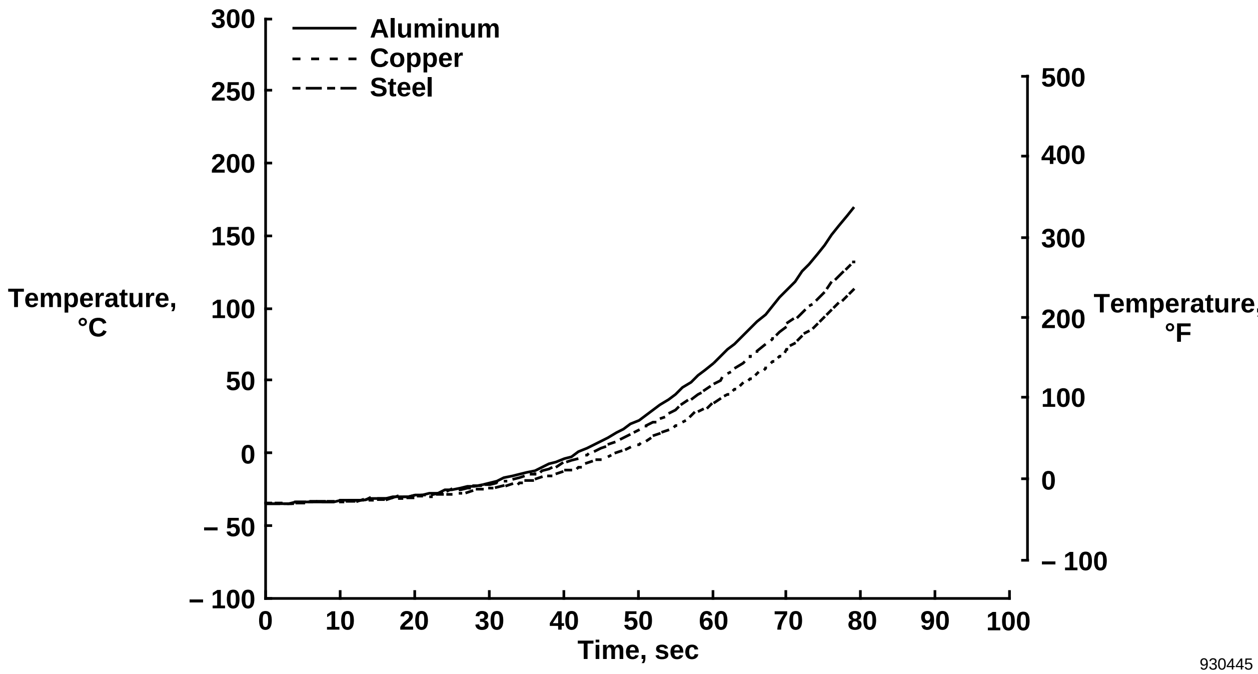

Fig. 9. Comparison of outer skin temperatures for three different materials.

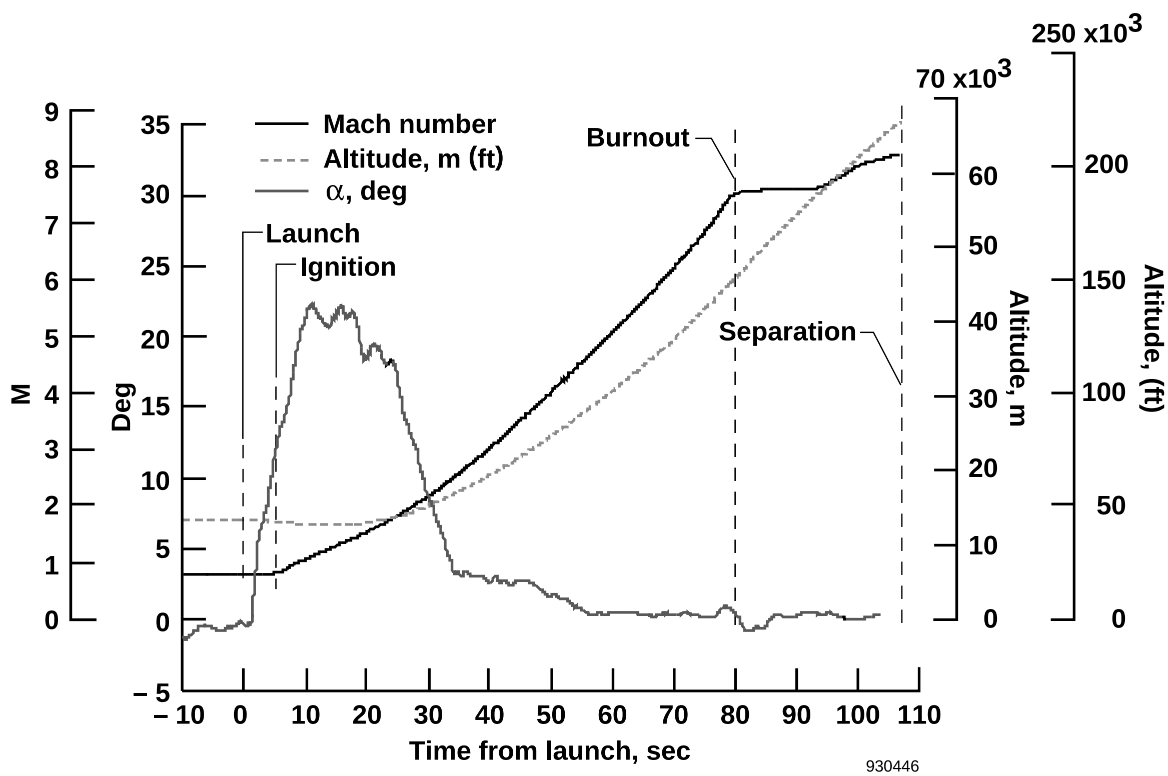

Fig. 10. Flight trajectory parameters of Mach number, angle-of-attack, and altitude.

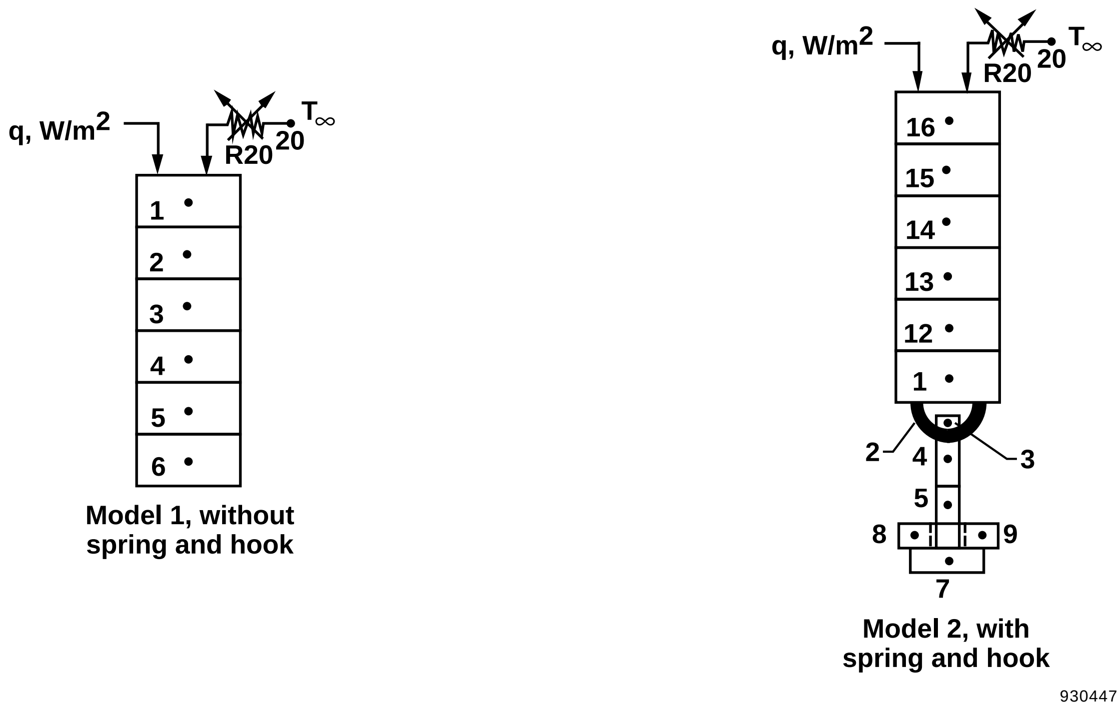

Fig. 11. One-dimensional thermal models of the glove skin with and without the spring and hook assembly.

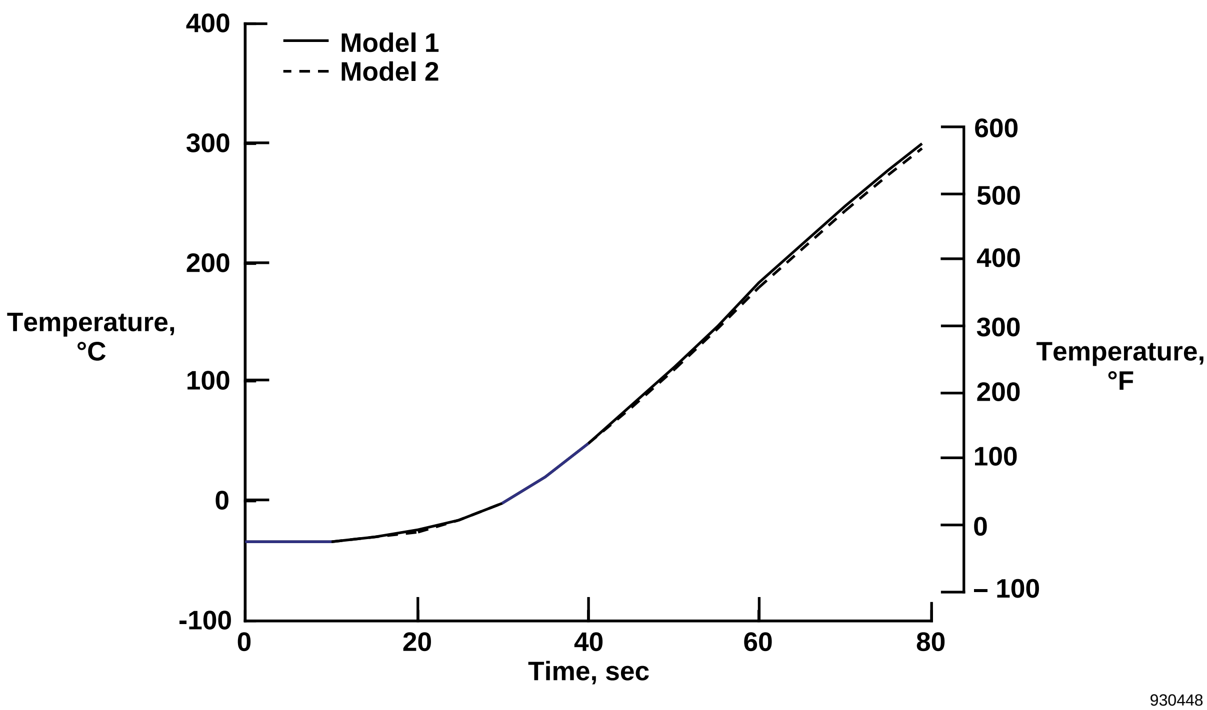

Fig. 12. Comparison of surface temperatures with and without the spring and hook assembly.

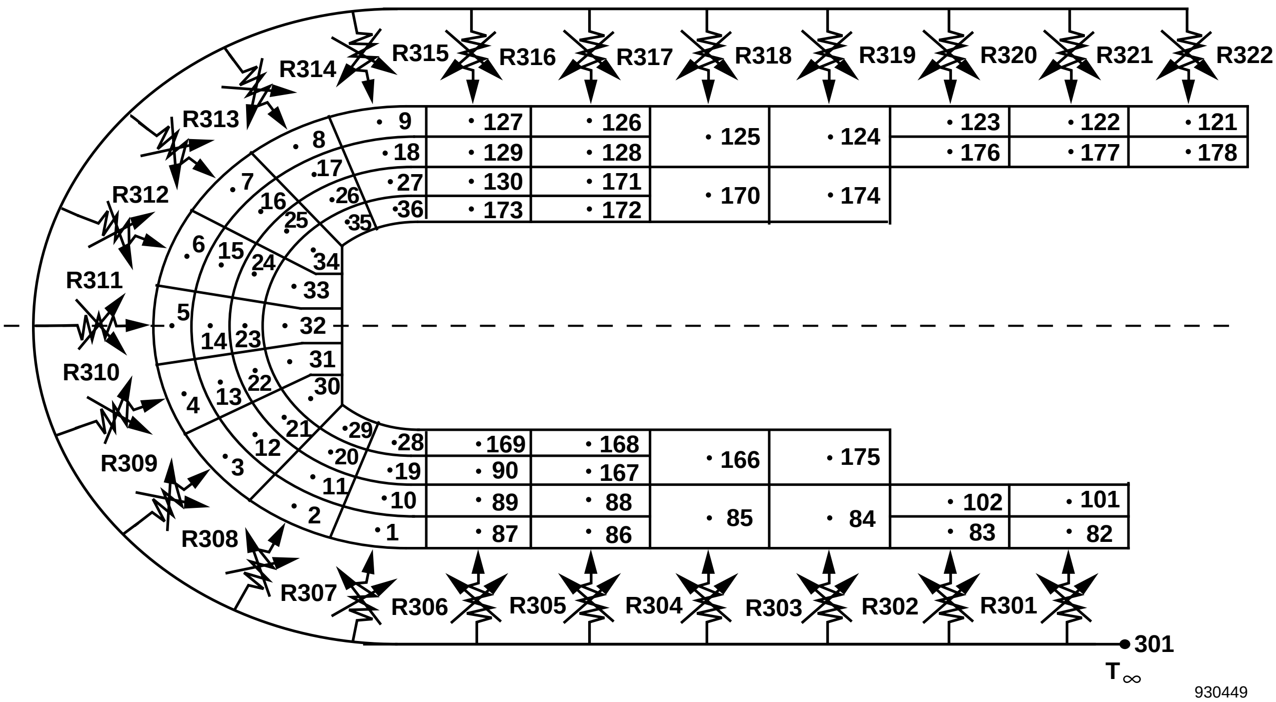

Fig. 13. Two-dimensional thermal model of the Pegasus® glove.

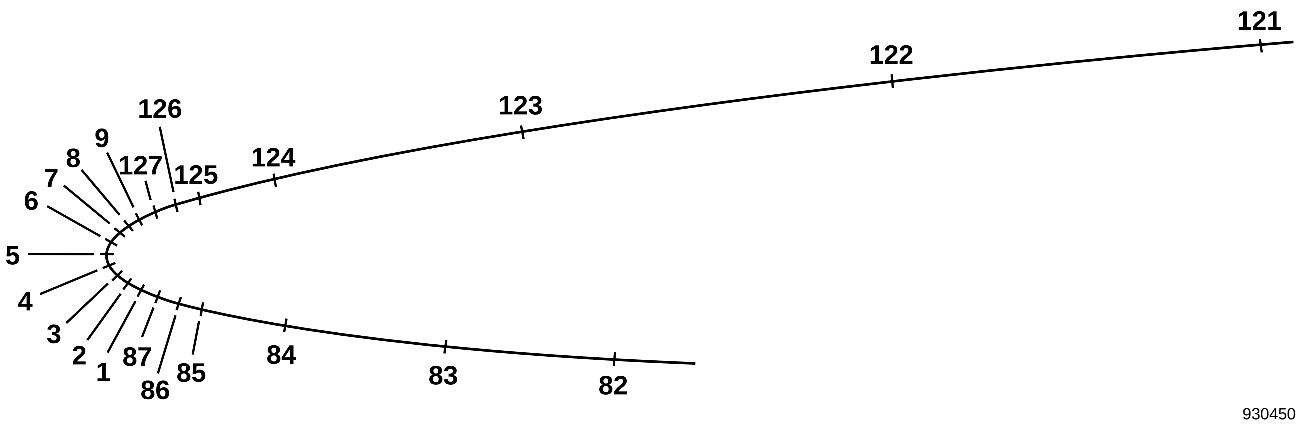

Fig. 14. Outer mold line of the metallic glove and locations of the thermal model nodes.

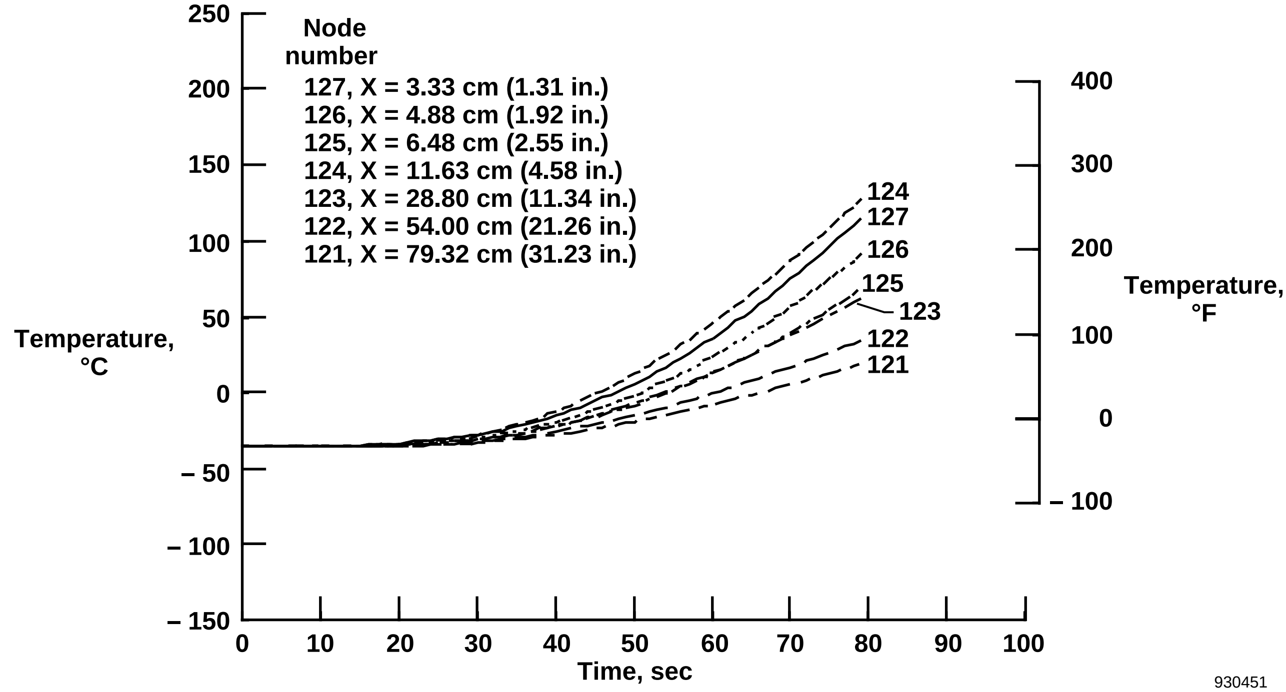

Fig. 15. Predicted surface temperatures using all laminar flow conditions.

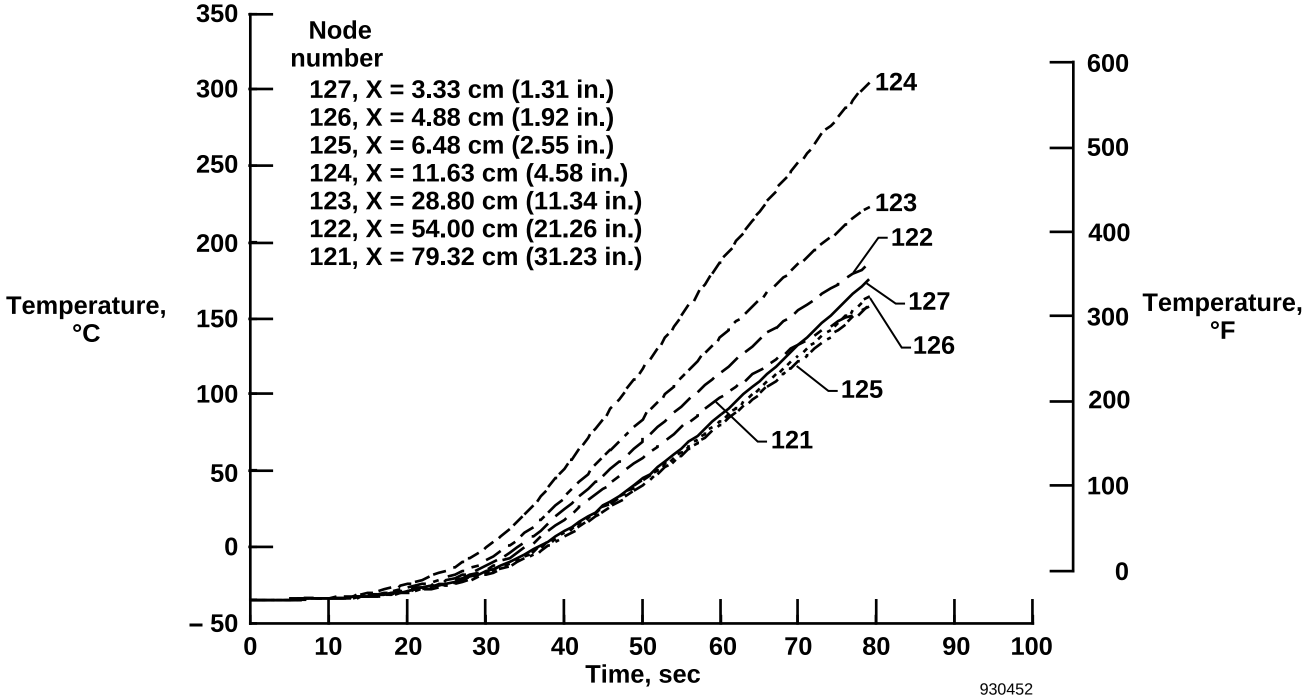

Fig. 16. Predicted surface temperatures using all turbulent flow conditions.

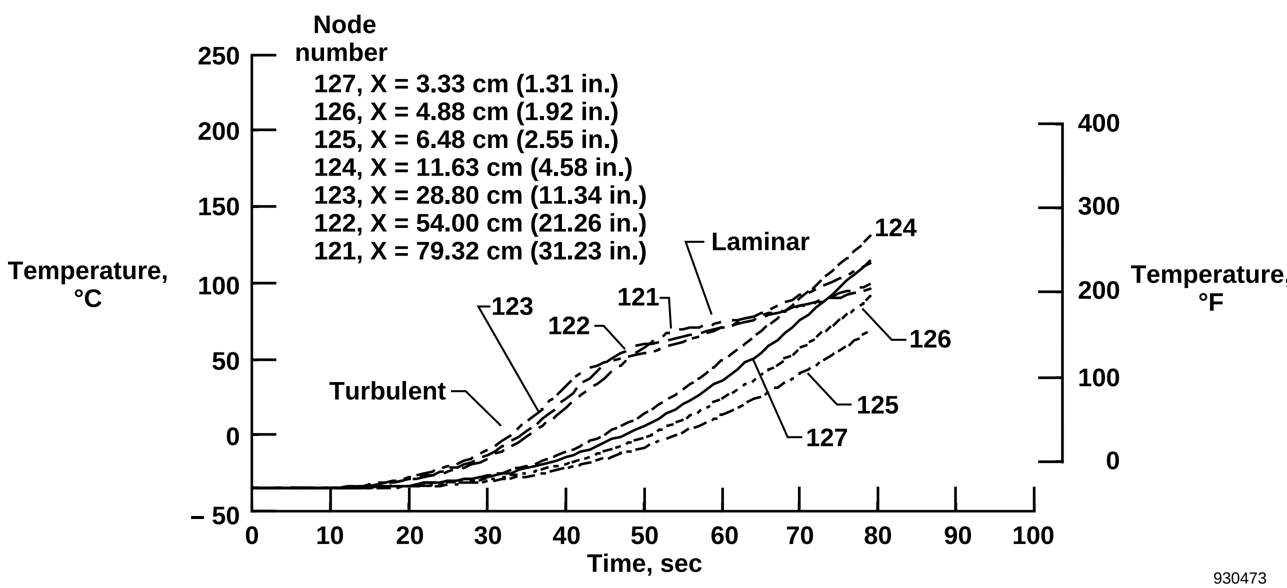

Fig. 17. Predicted surface temperatures using flow with transition.

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13. ABSTRACT (Maximum 200 words)

A boundary-layer transition experiment is proposed for a future flight mission of the air-launched Pegasus® space booster. The flight experiment requires attaching a glove assembly to the wing of the first-stage booster. The glove design consists of a spring and hook attachment system which allows for thermal growth of a steel 4130 skin. This paper presents results from one- and two-dimensional thermal analyses of the initial design. These analyses were performed to ensure the integrity of the wing and to define optimal materials for use in the glove. Results obtained from the thermal analysis using turbulent flow conditions showed a maximum temperature of approximately 305 °C (581 °F) and a chordwise temperature gradient of less than 8.9 °C/cm (40.5 °F/in.) for the critical areas in the upper glove skin. The temperatures obtained from these thermal analyses are well within the required temperature limits of the glove.

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